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An Interim Report

to
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EXECUTIVE SUMMARY

This research project is intended to develop an efficient system for reliably transmitting image and video data over low bit rate noisy channels. Possible applications of this research include real-time transmission of images by satellite, real-time visual feedback for teleoperated control of robots, terrestrial broadcasting of high-definition images, and transmission of images from deep space. The approach taken here is one of an integrated system design that exploits characteristics of image and video data and interactions between subsystems.

Accomplishment of this research project will result in a robust and bandwidth efficient image transmission system which fully exploits the redundancy in the data stream and the potential of system integration. The results will have great impact on image transmission systems which operate near channel capacity without the bandwidth needed for standard error control techniques to render satisfactory performance.

Figure 1 shows a typical image transmission system. The source coder removes the redundancy that exists in the image data to facilitate efficient transmission. However, compressed image data transmitted over noisy channels often result in unrecognizable images at the receiver. Existing methods typically try to resolve this problem by adding controlled redundancy back into the bit stream through channel coding. This effectively reduces the available channel bandwidth which in turn requires that the image data be more compactly represented. In essence, the existing methods trade off more controlled degradation due to a higher compression ratio to reduce the amount of uncontrolled degradation due to bit errors. The problem with such an approach is that the added degradation due to the higher compression ratio is always present. Thus pre- and post-processors are needed to improve the quality of image reconstruction. However, only limited improvement can typically be achieved by these processors.
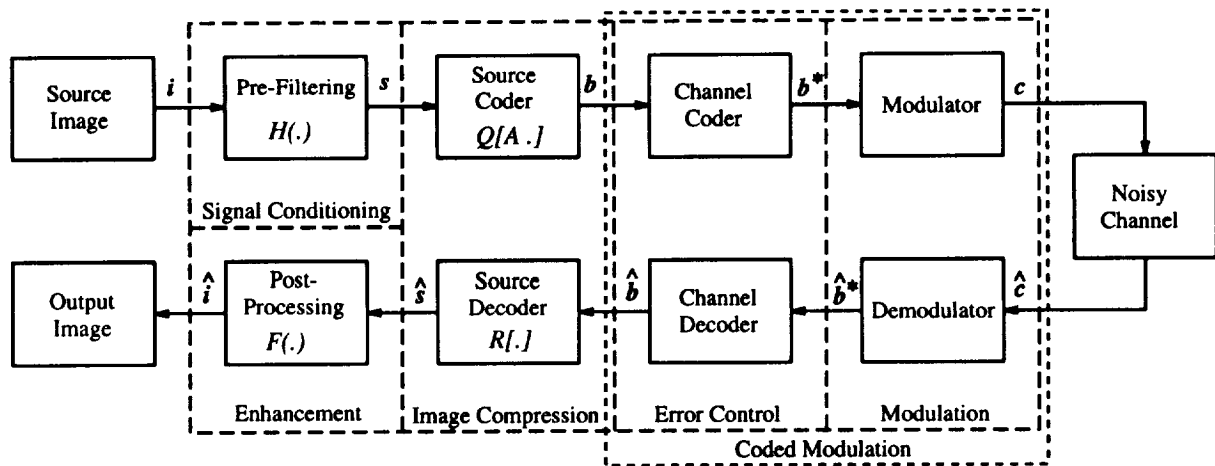

Figure 1: A Typical Image Communication System

The novelty of our approach is that it exploits the redundancy remaining in the bit-stream after compression to add robustness to the image decoder and it uses bandwidth efficient channel coding techniques to provide error protection without requiring additional

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compression. The key to the success of this approach is a detailed modeling of the complete system and the interactions between all its subsystems. Stochastic models are employed to characterize the noise as well as the original image to aid in the design of pre- and post-processors and coding/decoding schemes. The following realizations play an important role in our system development:

- Some bits in the image representation are more important than others. These bits must be better protected.

- Even in a compressed image format, redundancy is still present and can be used to detect when errors have occurred and to recover from them.

- Bandwidth efficient coding techniques, such as Trellis Coded Modulation (TCM) and Block Coded Modulation (BCM), will be used to control errors without reducing the channel bandwidth available to transmit the image data.

- Advanced image compression and enhancement techniques will be combined to provide the highest quality image given the limited bit-rate allowed. Higher quality will be obtained through the use of effective quantization schemes, such as vector quantization (VQ) and Trellis Coded Quantization (TCQ), and statistical reconstruction of the image.

The basic ideas behind the proposed approach are the following: Employ statistical-based image modeling to facilitate pre- and post-processing and error detection. Use spare redundancy that the source compression did not remove to add robustness. Implement coded modulation to improve bandwidth efficiency and noise rejection.

Over the last six months, progress has been made on various aspects of the project. Through our studies of the integrated system, a list-based iterative Trellis decoder has been developed. The decoder accepts feedback from a post-processor which can detect channel errors in the reconstructed image. The error detection is based on the Huber Markov random field image model for the compressed image. The compression scheme used here is that of JPEG (Joint Photographic Experts Group). Experiments were performed and the results are quite encouraging. The principal ideas here are extendable to other compression techniques. Some details of this progress are presented in Section I.

In addition, research was also performed on unequal error protection channel coding, subband vector quantization as a means of source coding, and post processing for reducing coding artifacts. Our studies on unequal error protection (UEP) coding for image transmission focused on examining the properties of the UEP capabilities of convolutional codes. The investigation of subband vector quantization employed a wavelet transform with special emphasis on exploiting interband redundancy. The outcome of this investigation included the development of three algorithms for subband vector quantization. The reduction of transform coding artifacts was studied with the aid of a non-Gaussian Markov random field model. This results in improved image decompression. These studies are summarized in Sections II-IV and the technical papers are included in the Appendices.

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DESCRIPTION OF RESEARCH

I. Robust Transmission of Compressed Images over Noisy Gaussian Channels

Many image communication systems have constraints on bandwidth, power, and time which prohibit transmission of uncompressed raw image data. Compressed image formats, however, are extremely sensitive to bit errors which can seriously degrade the quality of the image at the receiver.

The sensitivity of the compressed image representation to bit errors requires application of a channel code before transmission over noisy channels. To prevent uncontrolled degradation caused by channel errors, an error control channel code is applied to the compressed representation before transmission. The cost of the additional bits for redundancy in the channel code is paid for by an increased compression ratio which results in additional controlled quantization error.

Although the channel code greatly reduces the number of errors in the compressed image representation, a single error can still produce severe degradation in the quality of the received image. We have developed a post-processing method for reducing the visibility of quantization errors by making use of the Huber Markov random field image model. The robust image communication system proposed here uses this image model to detect errors in the compressed image representation. The post-processor sends feedback on suspected errors to the channel decoder for reconsideration. After channel decoding, the image is post-processed to reduce the visibility of quantization errors. Unlike other algorithms, this system coordinates channel error recovery with quantization error reduction. A new iterative channel decoder accepts error feedback from the new dual-purpose post-processor. A block diagram of the proposed image communication system is shown in Figure 2.

The following subsections present a more detailed summary of the proposed image communication system along with some experimental results to illustrate the concepts involved.
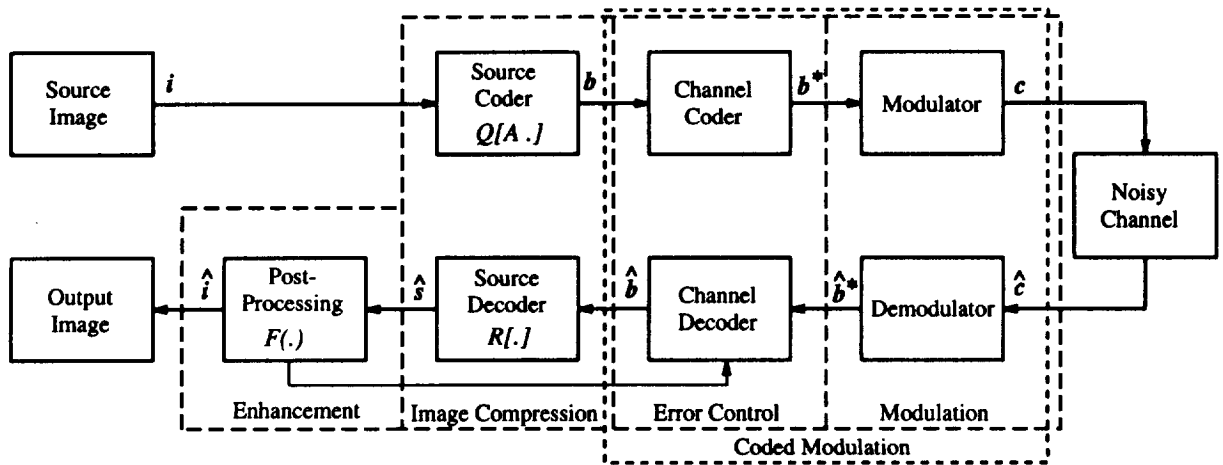

Figure 2: A Proposed Image Communication System

I.A Transmitter:

Standard solutions are used in the components of the transmitter. The input image i is compressed by the source encoder using the JPEG still image compression standard [9]. JPEG's extended sequential mode of operation is used with custom quantization tables, optimized Huffman coding tables, and restart markers after each row of blocks. The restart markers limit the influence of a channel error to a single row of blocks. The development of hardware implementations of JPEG encoders and decoders gives the JPEG standard an advantage over other approaches which have not been standardized. The compressed representation b is encoded for transmission over the noisy channel using a rate 1/2 convolutional code with constraint length 7 [5]. This code has good distance properties and has been used by NASA as a standard code for error control. The bit sequence b^* is then transmitted over the noisy channel using BPSK modulation.

I.B Receiver:

An iterative decoder based on a soft decision Viterbi trellis decoder interprets the noisy received bit-stream $\hat{b}^*$. The first iteration decodes the standard soft decision trellis to obtain the maximum likelihood sequence $\hat{b}$ given the received channel symbols. However, it is also known that $\hat{b}$ is a JPEG compressed image representation. Since correct decoding of the JPEG header information is critical to the correct reconstruction of the image, the second iteration redecodes the section of the trellis containing the JPEG header. The header syntax defined by the JPEG standard determines the value of many bits in the header and allows detection of incorrect header information. The known bits reduce the number of paths through the trellis and decrease the probability of decoding an incorrect path. This idea is similar to the pinned state decoder described in [1].

The third iteration considers the header to be known correctly and redecodes those sections of the trellis corresponding to entropy coded image data which have been flagged by the post-processor as possible sites for error events. When the post-processor questions the decoding of the trellis, the confidence with which each branch decision is made is entered into a list for each state along the most likely path in the region of doubt. This list is sorted with the least confident decision at the top. The branch decision with least confidence is overturned and the new path through the trellis is decoded, decompressed, and sent to the post-processor. The process proceeds iteratively. The trellis is redecoded with the next branch decision in the sorted list overturned, until the post-processor does not flag an error in this section or the end of the list is reached. Only one branch decision is overturned at a time since it is assumed the region of doubt contains only a single error event. To prevent erroneous redecoding due to false alarms signaled by the post-processor, the length of the list is limited to contain only branch decisions which were made with confidence less than a particular threshold value.

The errors are detected by the post-processor using the Huber-Markov Random Field (HMRF) image model. The HMRF model is characterized by a special form of the Gibbs distribution

$$Pr(\mathbf{x}) = \frac{1}{Z} \exp\{-\frac{1}{\lambda} \sum_{c \in \mathcal{C}} \rho_T(\mathbf{d}_c^t \mathbf{x})\}$$

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where λ is a scalar constant that is greater than zero, $\mathbf{d}_c$ is a collection of linear operators and the function $\rho_T(\cdot)$ is given by

$$\rho_T(u) = \begin{cases} u^2, & |u| \le T, \\ T^2 + 2T(|u| - T), & |u| > T; \end{cases}$$

To detect errors, this model is used to estimate the probability of each 8×8 block in the image. Blocks which are greatly effected by channel errors will have a large value for $\sum_{c \in C} \rho_T(\mathbf{d}_c^t \mathbf{x})$ and the probability of these blocks is quite small. Blocks which produce a large value are considered possible locations for errors and this information is fed back to the trellis decoder.

I.C Results

Figure 3 shows a 256×256 image of an airport which has been compressed to 0.26 bpp (bits per pixel) using the JPEG encoder. The channel SNR (signal-to-noise ratio) is 3 db per information bit. Figure 4 shows the effect of channel errors in the entropy coded image data. It can be seen in Figure 5 that 5 rows contain channel errors. The post-processor detected errors in 4 of these rows which were corrected (see Figure 6), while one of the errors was too small to be detected. The images are shown before quantization error reduction by the post-processor. Although a false alarm was detected in the second row from the bottom, no change in the image was made because the decoder reached the end of the list before an acceptable path was found.

I.D Conclusion

The new iterative trellis decoder is able to overcome channel noise using knowledge of compressed image syntax and the HMRF image model. The results are scalable to different degrees of quantization and can be extended to other compression techniques. Additional error protection is possible by using a longer constraint length convolutional code at the expense of additional receiver complexity. The next report shall include results for other compression ratios and average performance statistics.

II. Unequal Error Protection Coding for Image Transmission

In order to transmit encoded images over noisy channels, it is necessary to protect the data against transmission errors. In this case, erro control coding must be added to the image data prior to transmission. Since encoded image data may require several levels of protection, it is desirable to make use of Unequal Error Protection (UEP) channel codes. For example, it is usually necessary to provide a higher level of protection against errors in the header than in the data portion of an image. This would call for an error-correcting code with two levels of protection.

Most previous research on UEP coding has concentrated on the development of block codes. Since the transmission of image data requires the sending of many thousands of bits per image, this is an application where the advantages of convolutional or trellis codes can be exploited. Typically, convolutional or trellis codes are better suited to the transmission of large blocks of data than block codes, which are more efficient when transmitting relatively short blocks on the order of hundreds of bits. This is due to the fact that good block codes and efficient decoding algorithms are difficult to find for large block lengths. Convolutional
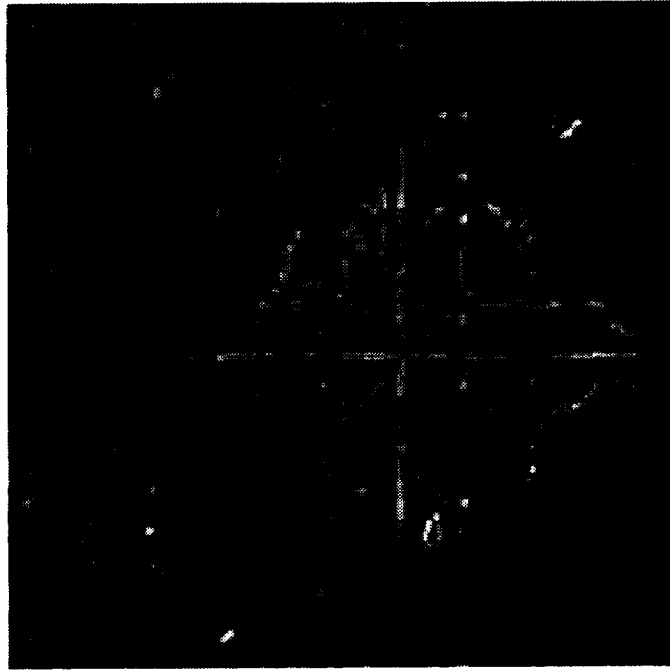
Figure 3: Airport Image, 256 × 256, Compressed by JPEG to 0.26 bpp, No Noise.

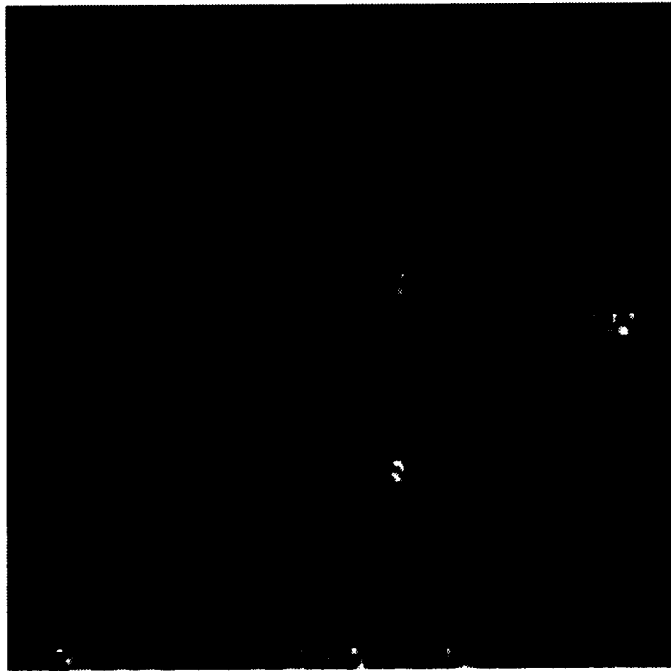Figure 4: Airport Image after 2nd Iteration of Trellis Decoder

Figure 5: Difference Image Between Noiseless Compressed Image and Reconstructed Image after 2nd Iteration.
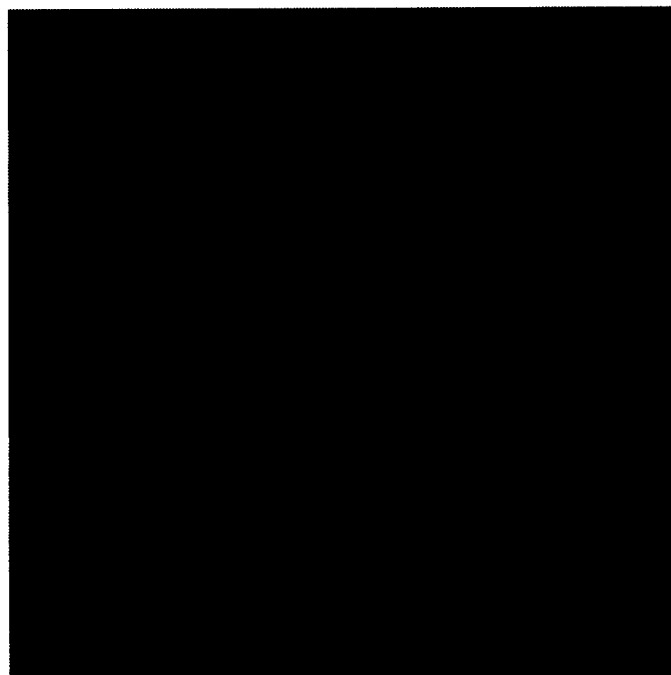

Figure 6: Difference Image Between Noiseless Compressed Image and Reconstructed Image after 3rd Iteration.

or trellis codes, on the other hand, are ideally suited to the transmission of large blocks of data. In addition, convolutional or trellis codes can easily take advantage of the 2-3dB soft decision performance improvement by using Viterbi or sequential decoding, whereas this is much more difficult to achieve with block codes. Therefore we have begun an investigation of the UEP capabilities of convolutional and trellis codes.

The paper included as Appendix A to this report examines the UEP capabilities of convolutional codes. An effective free distance vector is defined which characterizes the UEP properties of a particular code. A modified transfer function is developed and used to bound the Bit Error Rates (BER's) of the individual input bit positions in a convolutional encoder. UEP encoders for a variety of rates and decoder complexities are found and their performance is determined by computer simulation. We believe several of these new codes will be attractive in image transmission applications. Work is continuing on the UEP capabilities of bandwidth efficient trellis codes.

III. Subband Vector Quantization

Among a variety of image coding methods, vector quantization (VQ) and subband coding (SBC) have attracted considerable interest. This is mainly due to the fact that VQ can, in theory, always achieve better performance than scalar quantization (SQ), and SBC has been shown to achieve high compression ratios while maintaining good image visual quality. Much work has been done on combining these two methods. While many schemes use VQ to exploit the intra-band redundancy, little has been done to exploit the inter-band redundancy.

A disadvantage of VQ is that it often results in blocky images, similar to other block-based coding schemes. Over the last several years, various VQ techniques which aim to improve the visual quality of the reconstructed image have been developed. Typical techniques include classified VQ, variable rate VQ, subband VQ, etc. We examined the application of VQ in the frequency domain and showed that the subband-VQ approach is indeed viable for image compression.

We then investigated the application of VQ in the wavelet transform domain to exploit both intra-band and inter-band redundancy in subband coding. The focus here was on the exploitation of inter-band dependency. It was shown that VQ is particularly suitable and effective for coding the upper subbands. Three subband decomposition-based VQ coding schemes were developed to exploit the inter-band dependency by making full use of the extra flexibility that VQ has over SQ. A quadtree-based variable rate VQ scheme which takes full advantage of the inter-band as well as the intra-band redundancy was devised. This scheme takes advantage of the edge feature separation property of subband decomposition and employs a product-code-like VQ approach to fully exploit the inter-band redundancy. Then a more easily implementable alternative based on an efficient block-based edge estimation technique was employed to overcome the complexities of the first scheme. Finally, a predictive VQ scheme, formulated in the context of finite state VQ was proposed to further exploit the dependency among different subbands. An efficient bit allocation procedure was incorporated. Simulation results showed that these three hybrid techniques have advantages, in terms of peak signal-to-noise ratio and complexity, over other existing subband VQ approaches. Technical details of this study are given in Appendix B.

IV. Improved Image Decompression for Reduced Transform Coding Artifacts

The perceived quality of images reconstructed from low bit rate compression is often severely degraded by the appearance of transform coding artifacts. Our study of this issue has resulted in a method for producing higher quality reconstructed images based on stochastic models for the image data. Probabilistic models are used for both the noise introduced by coding and for a *good* image. The restored image is the maximum a posteriori (MAP) estimate based on these models.

Quantization (scalar or vector) partitions the transform coefficient space and maps all points in a partition cell to a representative reconstruction point, usually taken as the centroid of the cell. The proposed image estimation technique selects the reconstruction point within the quantization partition cell which results in a reconstructed image that best fits a non-Gaussian Markov Random Field (MRF) image model. This approach leads to a convex constrained optimization problem which can be solved iteratively. At each iteration, the gradient projection method is used to update the estimate based on the image model. In the transform domain, the resulting coefficient reconstruction points are projected to the particular quantization partition cells defined by the compressed image.

Experiments have been performed for images compressed with scalar quantization of block discrete cosine transform (i.e., JPEG) and with vector quantization of subband wavelet transform. The proposed image decompression provides a reconstructed image with reduced visibility of transform coding artifacts and superior perceived quality. This in turn allows for higher compression ratios. A technical paper based on this study is included in Appendix C.

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WORK IN PROGRESS

Average performance statistics are being measured for the iterative feedback decoder discussed in Section I.B. The performance of this system depends on the ability of the post-processor to detect artifacts of channel errors in the reconstructed image. Statistical signal detection methods are being studied for the purpose of improving channel error detection and false alarm rejection. The effect of varying compression ratios on performance is also being investigated, and we are also exploring the use of transmitted side information to improve error detection.

In order to detect artifacts of channel errors in the decoded image, it is desirable to design the channel code such that the more likely channel errors result in large (easily detected) deviations from the image model in the reconstructed image. This will be accomplished by jointly selecting the source code and channel code during the design phase and by providing updated measures of the perceptual similarity between source codewords to the channel encoder for use in channel symbol assignment.

Finally, advanced quantization and modulation techniques such as VQ, TCQ, BCM, and TCM provide significant advantages over uniform scalar quantization and binary communication. The employment of VQ and TCQ is being considered for integration into the system design, and the use of BCM and TCM for bandwidth efficiency as well as noise protection is being pursued in conjunction with joint quantization-modulation techniques.